LEVELIZED COST OF ELECTRICITY: PV AND CPV IN COMPARISON TO OTHER TECHNOLOGIES

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ABSTRACT: This paper presents the findings of the Fraunhofer ISE study on the levelized cost of electricity (LCOE) of renewable energy technologies with a focus on PV (Fraunhofer ISE, 2013). It predicts future cost and market developments through 2030 based on technology-specific learning curves and market scenarios. Photovoltaics (PV) are assessed in Germany. Moreover, the solar technologies PV and concentrating photovoltaics (CPV) are analyzed in regions with higher solar irradiation. They are compared to other renewable energy technologies such as (onshore and offshore) wind power, concentrating solar power (CSP) and biogas on the basis of common market financing costs. The current and future LCOE for new conventional power plants (brown coal, hard coal, combined cycle gas turbine (CCGT), oil-fired power plants) are calculated as a reference.

Keywords: PV, CPV, LCOE, cost analysis

1 Introduction

In contrast to the tendency of increasing energy prices for fossil and nuclear power sources, levelized cost of electricity (LCOE) of all renewable energy technologies have been falling continuously for decades. This development is driven by technological innovations such as the use of less-expensive and better-performing materials, reduced material consumption, more-efficient production processes, increasing efficiencies as well as automated mass production of components. For that reason, the objective of this study is to analyze the current and possible future cost situation in terms of the LCOE. This paper is an extraction of the specific findings for PV and CPV from the study “Levelized Cost of Electricity - Renewable Energy Technologies” which was published by Fraunhofer ISE in November 2013 (Fraunhofer ISE, 2013).

The technologies photovoltaics (PV) and concentrating photovoltaics CPV are assessed and compared on the basis of historically documented learning curves and conventional market financing costs. In order to be able to realistically represent the usual variations in market prices and fluctuations in full load hours within the respective technologies, upper and lower price limits are stated (Fraunhofer ISE, 2013).

2 Approach and Method

This paper evaluates the current and future market development of PV and CPV regarding various aspects. In a first step a cost analysis is conducted and technology-specific LCOE (Status: 3Q 2013) is calculated for different local conditions, especially with different solar irradiations. Furthermore an assessment of the different technological and financial parameters for PV and CPV is made using sensitivity analyses.

In addition to the analysis of the LCOE for PV and CPV in 2013, it is possible, with the help of market projections through 2020 and 2030 and generation of learning curve models to develop a forecast about the future development of PV and CPV system prices. Consequently, LCOE for PV and CPV can be forecasted as well.

The calculation of the average LCOE is done on the basis of the net present value method, in which the expenses for investment and the payment streams from earnings and expenditures during the plant’s lifetime are calculated based on discounting. The annual total expenditures over the entire operational lifetime are comprised of the investment expenditures and the operating costs accumulating over the operational lifetime. For calculating the LCOE for new plants, the following applies (Konstantin 2009):

Equation 1:

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^t}}$$

As Equation 1 shows, the level of LCOE (in EUR/kWh) depends significantly on the following parameters:

Specific investment expenditures for the construction and installation of power plants in EUR (I_0) with upper and lower limits (see Table I in the appendix). The determination is based on current power plant and market data.

Annual total operating costs during the power plant’s operational life time in EUR in year t (A_t) as well as the economic operational lifetime in years (n).

The produced quantity of electricity in the respective year in kWh ($M_{t,el}$) which strongly depends on the local conditions with regard to typical irradiation, wind speeds and full load hours in the energy system.

The financing conditions such as earnings calculated on the financial market and maturity periods based on technology-specific risk surcharges and country-specific financing conditions. Taking also into account the respective shares of external and equity-based financing. This results into the projects real interest rate in % (i).

Furthermore the index (t) denotes the year of lifetime.

3 Data input

The main data input to the analysis here is the market development in the past and in the future, the cost analysis of the technologies and the operation parameter in terms of energy output. The data input for all technologies is presented in detail in the study

(Fraunhofer ISE, 2013). The most important data sheets can also be found in the appendix.

Table I in the appendix shows the amounts of investment in EUR/kW (nominal capacity) for all technologies considered that are determined based on market research on currently installed power plants in Germany as well as taking external market studies into account. Within each technology the system costs are distinguished based on power plant size and power plant configuration.

According to the market studies investigated here, the global market demand for PV will continue to see strong growth in the coming years. The basis for the market forecast came from "Global Market Outlook for Photovoltaics" of the European Photovoltaic Industry Association (EPIA 2013) and a Technology Roadmap from the IEA from the year 2010. In the EPIA study, two scenarios were presented: "Business as Usual" and "Policy Driven". They predict the market development through 2017. These scenarios were extrapolated for the years 2018 to 2030 with an annual growth rate of 10% (Business as Usual) or 15% (Policy Driven). Figure 8 in the appendix shows the extrapolated market forecasts through 2030 for EPIA - Policy Driven (2013) and IEA - Roadmap Vision (2010), as well as an average value scenario for available market forecasts.

The financing and operational parameters are analyzed in detail and adapted to the risk and investor structure of the individual technologies, since the selected discount rate has considerable influence on the calculated LCOE. The input parameters for the calculation of the economic efficiency are shown in Table II in the appendix. The discount rates in this study are determined for each technology through the usual capital costs on the market (weighted average costs of capital - WACC) for the respective investment and are comprised in part of external capital interest and equity capital earnings. Large power plants that are built and operated by large institutional investors have, due to the amount of investment return required by the investor, a higher WACC than small power plants or medium-sized power plants that are constructed by private persons or business partnerships.

In addition to the location, system specific full load hours and energy output of each technology (see

	Regions with high solar irradiation			
	PV small	PV large/ utility	CSP	CPV
Lifetime [in years]	25	25	25	25
Share of equity	20%	20%	30%	30%
Share of debt	80%	80%	70%	70%
Return on equity	8.0%	10.0%	13.5%	13.5%
Interest rate on debt	6.0%	6.0%	7.0%	7.0%
$WACC_{nom}$ (Weighted Average Cost of Capital)	6.4%	6.8%	9.7% (8.8%)*	9.7% (8.2%)*
$WACC_{real}$	4.7%	4.7%	7.5% (6.7%)*	7.5% (6.1%)*
Annual operation costs [in Euro/kWh]			0.028	
Annual fixed operation costs [in Euro/kW]	35	35		35
Annual reduction of electricity output	0.2%	0.2%	0.2%	0.2%
CO_2 emissions [in kg/kWh]				
Fuel costs considered				

Table III,
Table IV and Table VI in the appendix for the corresponding numbers), the results for conventional power plants strongly depend on the assumptions for operation costs. The price development of fossil fuels and CO_2 emission allowances significantly influences the future LCOE. Price for brown coal is expected to be stable, whereas price for hard coal and natural gas is expected to increase. CO_2 emission allowances are assumed to be at around 50 EUR/t in 2050. All relevant assumptions are stated in Table V and Table VII in the appendix.

4 Results

The values of current PV LCOE are shown in Figure 1 and Figure 2 for various power plant sizes and costs at different irradiation values (in Germany and regions with high irradiation). The number following power plant size stands for the annual global horizontal irradiance at the power plant location in kWh/(m²a). Power plants in Northern Germany produce approximately 1000 kWh/(m²a), while power plants in Southern Germany supply up to 1190 kWh/(m²a). In Southern Spain and the MENA countries up to 1790 kWh/(m²a) are achieved. The strong decline in prices for these power plant investments has a substantial influence on the development of PV LCOE. Even in Northern Germany, it is already possible to achieve a LCOE of 0.14 EUR/kWh and below. Consequently, the costs for photovoltaically generated electricity from all types of PV power plants in Germany are beneath the average household price of electricity. In the meantime, at locations in Southern Germany even small PV systems achieve a LCOE between 0.10 and 0.12 EUR/kWh. Since all PV technologies, however, still have a clear potential for cost reduction, one must count on a continued decrease in the LCOE in the medium to long term.

Figure 1: LCOE of PV plants in Germany based on system type and irradiation (GHI in kWh/(m²a)) in 2013, (Fraunhofer ISE, 2013).

At locations with high global horizontal irradiation (GHI) of 1800 kWh/(m²a) in Southern Spain and/or 2000 kWh/(m²a) such as in the MENA countries, the LCOE fell from 0.10 to 0.06 Euro/kWh (Figure 2). In regions with an irradiation of 1450 kWh/(m²a) such as in France, the LCOE lies at approximately 0.08 to 0.12 Euro/kWh. The higher financing costs at locations such as Spain or the MENA countries, however, increase the LCOE, so that the advantage of considerably higher irradiation is lost in part.

Figure 2: LCOE of various PV plant types at three locations with high solar irradiation (GHI in kWh/(m²a)) in 2013, (Fraunhofer ISE, 2013).

A sensitivity analysis for a small PV plant in Germany demonstrates the strong dependency of the LCOE on irradiation and specific investments (see Figure 3).

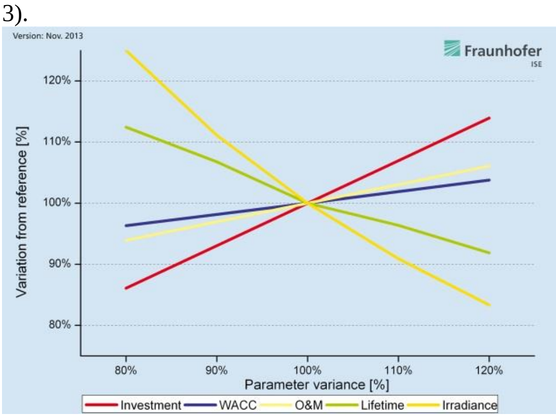

Figure 3: Sensitivity analysis of a small PV system with a GHI of 1050 kWh/(m²a) and investment of 1500 Euro/kW, (Fraunhofer ISE, 2013).

Current system prices, including installation for CPV power plants with a capacity of 10 MW, lie between 1400 and 2200 EUR/kW (Sources: GTM 2013, industry survey). The large range of prices results from the different technological concepts as well as the still-young and regionally variable markets. Today, the calculated LCOE from 0.102 to 0.148 kWh/EUR for a location with a DNI of 2000 kWh/(m²a) can already provide a basis for comparison with the analyzed values for PV utility-scale power plants and CSP in spite of the small market volume (see Figure 4).

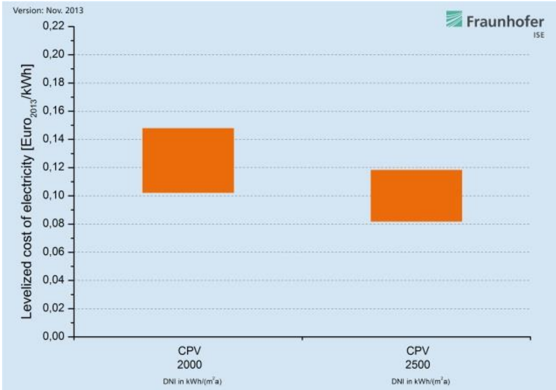

Figure 4: LCOE of CPV by irradiation (DNI in kWh/(m²a)) in 2013, (Fraunhofer ISE, 2013).

Similar to PV, the LCOE of CPV strongly depends on the specific investment and irradiance (Figure 5).

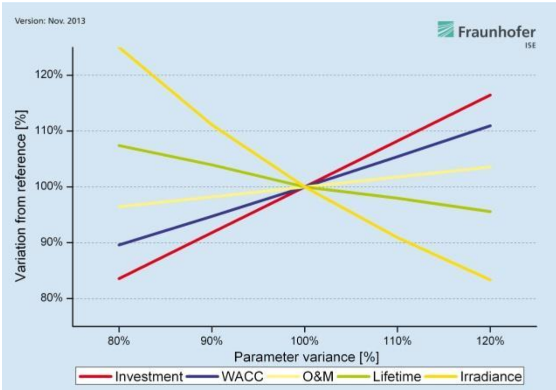

Figure 5: Sensitivity analysis of CPV (irradiation DNI = 2000 kWh/(m²a), investment = 1800 Euro/kW, (Fraunhofer ISE, 2013).

Today, nearly all newly installed PV power plants in Germany can generate power for under 0.15 EUR/kWh. At an annual irradiation of 1000 kWh/(m²a), even the costs for smaller rooftop systems will fall under the 0.12 EUR/kWh mark by 2018. Larger utility-scale power plants with an annual irradiation of 1200 kWh/(m²a) will already be generating their power for less than 0.08 EUR/kWh. Starting in 2025 the LCOE of both plant types will fall below the value of 0.11 or 0.06 EUR/kWh respectively. Starting in 2020, utility-scale PV plants in Southern Germany will generate power less expensively than likewise newly installed hard coal or CCGT power plants, which then achieve LCOE of 0.08 to 0.12 EUR/kWh. The plant prices for utility-scale PV plants will sink to 570 EUR/kW and for small plants to values at the range of 800 to 1000 EUR/kW.

Depending on the wind conditions at the location, comparable prices can be achieved for onshore wind power plants as for PV power plants at good locations. In the long term, only locations with annual full load hours exceeding 2000 hours can achieve a lower LCOE than the best PV power plants. From the current LCOE between 0.044 EUR/kWh and 0.107 EUR/kWh, the costs will sink in the long-term to 0.043 and 0.101 EUR/kWh. Generally, in Germany PV power plants at high-irradiation locations and wind power at favorable onshore locations will have the lowest LCOE in the long-term. Both technologies will be able to undercut the LCOE from fossil power plants by 2030. The development of

LCOE until 2030 for the different generation technologies is shown in Figure 6.

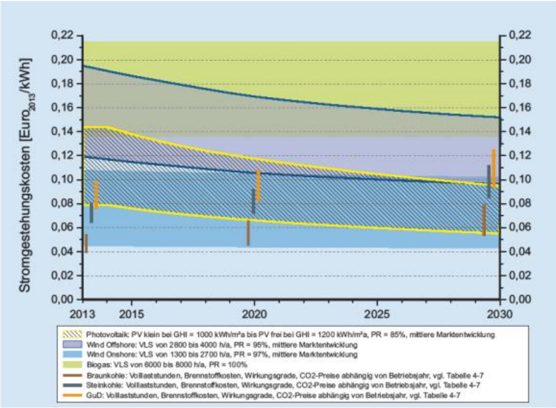

Figure 6: Forecast of the development of LCOE of renewable energy technologies as well as conventional power plants in Germany by 2030, (Fraunhofer ISE, 2013).

As shown in Figure 7, in the pure cost comparison for 2013 at locations with high irradiation (2000 kWh/(m²a)), PV shows lower LCOE than CSP and CPV. Due to the weaker market growth compared to PV, the LCOE of CSP plants with integrated thermal storage (up to 3600 full load hours) is currently below 0.19 EUR/kWh, while utility-scale PV power plants achieve a LCOE of less than 0.10 EUR/kWh at the same irradiation. Depending on the irradiation, CPV plants lie between 0.08 and 0.14 EUR/kWh. By 2030, the LCOE from PV can sink to values between 0.04 EUR/kWh and 0.07 EUR/kWh. In the case of CPV, a cost decrease to values between 0.040 EUR/kWh and 0.076 EUR/kWh would also be possible.

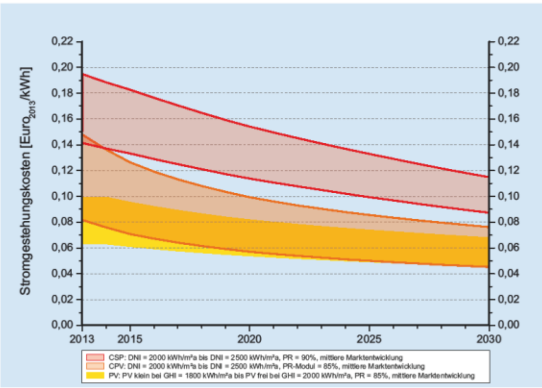

Figure 7: Development of the LCOE of PV, CSP and CPV at locations with high solar irradiation, (Fraunhofer ISE, 2013).

To conclude on the LCOE forecast for PV and CPV, the LCOE of both technologies show high competitive values compared to other electricity generation technologies. Also in Germany (with its lower irradiance), LCOE of PV is competitive to wind onshore and conventional power generation technologies. By realizing strong cost reductions during the last years also CPV reaches values at around 0.10 EUR/kWh. If further cost reductions and increase of efficiency takes place, the CPV will increase its number of installations in countries with high irradiance.

5 References

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6 Appendix

Table I: Investments in EUR/kW for current power plant installations

[Euro/kW]	PV small	PV large	PV utility scale	Wind onshore	Wind offshore	Biogas	CPV
Investment 2013 low	1300	1000	1000	1000	3400	3000	1400
Investment 2013 high	1800	1700	1400	1800	4500	5000	2200
[Euro/kW]	CSP-Parabol without storage	CSP-Parabol with 8h-storage	CSP-Fresnel without storage	CSP-Tower with 8h-storage	Brown coal	Hard coal	Com-bined cycle
Investment 2013 low	2800	5200	2500	6000	1250	1100	550
Investment 2013 high	4900	6600	3300	7000	1800	1600	1100

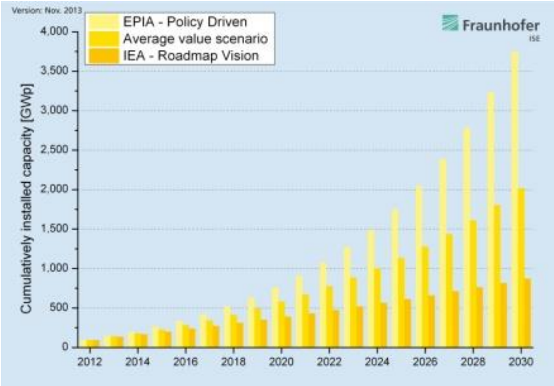

Figure 8: Market forecast for PV 2012-2030 according to IEA (2010), EPIA (2013) and own calculations, (Fraunhofer ISE, 2013).

Table II: Input parameters for calculation of economic efficiency, (Fraunhofer ISE, 2013).

	Germany								
	PV small	PV large	PV utility scale	Wind On-shore	Wind Off-shore	Brown coal	Hard coal	Com-bined cycle	Bio-mass
Lifetime [in years]	25	25	25	20	20	40	40	30	20
Share of equity	20%	20%	20%	30%	40%	40%	40%	40%	30%
Share of debt	80%	80%	80%	70%	60%	60%	60%	60%	70%
Return on equity	6.0%	8.0%	8.0%	9.0%	14.0%	13.5%	13.5%	13.5%	9.0%
Interest rate on debt	4.0%	4.0%	4.0%	4.5%	7.0%	6.0%	6.0%	6.0%	4.5%
$WACC_{nom}$ (Weighted Average Cost of Capital)	4.4%	4.8%	4.8%	5.9%	9.8% (8.8%)*	9.0%	9.0%	9.0%	6.2%
$WACC_{real}$	2.4%	2.8%	2.8%	3.8%	(6.7%)*	6.9%	6.9%	6.9%	4.1%
Annual operation costs [in Euro/kWh]				0.018	0.035				
Annual fixed operation costs [in Euro/kW]	35	35	35			36	32	22	175
Annual reduction of electricity output	0.2%	0.2%	0.2%	0.0%	0.0%				
CO_2 emissions [in kg/kWh]						0.36	0.34	0.20	
Fuel costs considered						x	x	x	x

	Regions with high solar irradiation			
	PV small	PV large/ utility	CSP	CPV
Lifetime [in years]	25	25	25	25
Share of equity	20%	20%	30%	30%
Share of debt	80%	80%	70%	70%
Return on equity	8.0%	10.0%	13.5%	13.5%
Interest rate on debt	6.0%	6.0%	7.0%	7.0%
$WACC_{nom}$ (Weighted Average Cost of Capital)	6.4%	6.8%	9.7% (8.8%)*	9.7% (8.2%)*
$WACC_{real}$	4.7%	4.7%	7.5% (6.7%)*	7.5% (6.1%)*
Annual operation costs [in Euro/kWh]			0.028	
Annual fixed operation costs [in Euro/kW]	35	35		35
Annual reduction of electricity output	0.2%	0.2%	0.2%	0.2%
CO_2 emissions [in kg/kWh]				
Fuel costs considered				

Table III: Annual yields at typical locations of PV, CSP and wind power, (Fraunhofer ISE, 2013).

PV system (standard module)	Irradiation on PV module at optimal angle	Electricity output per 1 kWp
Germany North (GHI 1000 kWh/(m²a))	1150 kWh/(m²a)	1000 kWh/a
Germany Center and East (GHI 1050 kWh/(m²a))	1210 kWh/(m²a)	1040 kWh/a
Germany South (GHI 1200 kWh/(m²a))	1380 kWh/(m²a)	1190 kWh/a
Southern France (GHI 1450 kWh/(m²a))	1670 kWh/(m²a)	1380 kWh/a
Southern Spain (GHI 1800 kWh/(m²a))	2070 kWh/(m²a)	1680 kWh/a
MENA (GHI 2000 kWh/(m²a))	2300 kWh/(m²a)	1790 kWh/a
Wind power plant (2 - 5 MW)	Full load hours of wind	Electricity output per 1 kW
Onshore: Germany center and south (wind speed 5.3 m/s; 130m hub height)	1300 h/a	1300 kWh/a
Onshore: Germany near the coast and strong wind locations (wind speed 6.3 m/s; 80m hub height)	2000 h/a	2000 kWh/a
Onshore: Atlantic coastline UK (wind speed 7.7 m/s; 80m hub height)	2700 h/a	2700 kWh/a
Offshore: Areas near the coast (wind speed 7.9 m/s; 80m hub height)	2800 h/a	2800 kWh/a
Offshore: Medium distance to coastline (wind speed 8.7 m/s)	3200 h/a	3200 kWh/a
Offshore: Locations far from the coast (wind speed 9.5 m/s)	3600 h/a	3600 kWh/a
Offshore: Very good locations (wind speed 10.3 m/s)	4000 h/a	4000 kWh/a
CSP power plant (100 MW)	Direct normal irradiation (DNI)	Electricity output per 1 kW (additionally dependent on storage size, 8h)
Parabolic with storage (Southern Spain)	2000 kWh/(m²a)	3300 kWh/a
Parabolic with storage (MENA)	2500 kWh/(m²a)	4050 kWh/a
Fresnel (Southern Spain)	2000 kWh/(m²a)	1850 kWh/a
Fresnel (MENA)	2500 kWh/(m²a)	2270 kWh/a
Solar tower with storage (Southern Spain)	2000 kWh/(m²a)	3240 kWh/a
Solar tower with storage (MENA)	2500 kWh/(m²a)	3980 kWh/a
CPV power plant	Direct normal irradiation (DNI)	Electricity output per 1 kWp
CPV (Southern Spain)	2000 kWh/(m²a)	1560 kWh/a
CPV (MENA)	2500 kWh/(m²a)	2000 kWh/a

Table IV: Development of full load hours of conventional power plants, (Fraunhofer ISE, 2013).

Development of full load hours (FLH) of conventional power plants	Brown coal	Hard coal	Combined cycle
FLH 2013 medium	7100	6000	3500
FLH 2013 low	6600	5500	3000
FLH 2013 high	7600	6500	4000
FLH 2020 medium	6800	5700	3500
FLH 2020 low	6300	5200	3000
FLH 2020 high	7300	6200	4000
FLH 2030 medium	5800	4800	3100
FLH 2030 low	5300	4300	2600
FLH 2030 high	6300	5300	3600
FLH 2040 medium	4900	4100	2900
FLH 2040 low	4400	3600	2400
FLH 2040 high	5400	4600	3400
FLH 2050 medium	4300	3600	2600
FLH 2050 low	3800	3100	2100
FLH 2050 high	4800	4100	3100

Table V: Assumptions about fuel prices, (Fraunhofer ISE, 2013).

Fuel price [$Euro_{2013}$/kWh]	2013	2020		2030		2040	2050
		lower	upper	lower	upper		
Brown coal	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016
Hard coal	0.0114	0.0103	0.0114	0.0112	0.0175	0.0188	0.0200
Natural gas	0.0287	0.0276	0.0320	0.0287	0.0363	0.0398	0.0470
Substrate for Biomass	0.0300	0.0250	0.0400	0.0250	0.0400	0.0400	0.0400

Table VI: Development of efficiency in large power plants, (Fraunhofer ISE, 2013).

Development of energy conversion efficieny of conventional power plants	2013	2020	2030
Brown coal	45.0%	46.5%	48.5%
Hard coal	46.0%	50.0%	51.0%
Combined cycle	60.0%	61.0%	62.0%
Biomass	40.0%	40.0%	40.0%

Table VII: CO_2 allowance price, (Fraunhofer ISE, 2013).

CO_2 allowance price [$Euro_{2013}/tCO_2$]	2013	2020	2030	2040	2050
lower value (own calculation)	5.3	17	28	35	40
upper value (Prognos)	5.3	21.7	42	50.7	55
medium value	5.3	19.3	35	42.9	47.5